

Clues to Radial Migration from the Properties of Outer Disks

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Abstract. The outer disks of galaxies present a unique laboratory for studying the process of disk formation. A considerable fraction of observed disks exhibit a break in their surface brightness profiles. The ubiquity of these features points to a crucial aspect of disk formation which must be explained. Recent theoretical work suggests that such breaks are related to significant amounts of radial migration. We discuss the current observational evidence which supports this picture.

Keywords. galaxies: kinematics and dynamics, galaxies: spiral, galaxies: stellar content, galaxies: structure, stellar dynamics

1. Introduction

The majority of the thin disk forms out of gas quiescently cooling and collapsing inside the host dark matter halo following the last major merger (Brook et al. 2004). While the inner parts of the stellar thin disk are entangled with the pre-merger material, the outer parts evolve in relative solitude, modulo interactions with substructure components present within the host halo. The outer parts of galactic disks therefore provide us with a direct view of disk assembly in progress.

Since van der Kruit (1979, 1987) it has been known that the surface brightness profiles of disk galaxies may not always follow a simple single-exponential law. In a recent work using data from the Sloan Digital Sky Survey (SDSS), Pohlen & Trujillo (2006) showed that $\sim 60\%$ of nearby disk galaxies have downward-bending surface brightness breaks, traditionally termed “truncations”. Disk breaks have also been observed in the distant universe out to a redshift of $z \sim 1$ (Pérez 2004; Trujillo & Pohlen 2005; Azzollini et al. 2008a), further implying that they are a generic feature of disk formation.

Several theories for the formation of downward-bending breaks have been suggested. The most common interpretations include angular momentum-limited collapse (van der Kruit 1987; van den Bosch 2001), star formation threshold either due to a critical gas density (Kennicutt 1989) or a lack of a cool equilibrium ISM phase (Elmegreen & Parravano 1994; Schaye 2004). Alternatively, breaks have also been attributed to angular momentum redistribution (Debattista et al. 2006; Foyle et al. 2008).

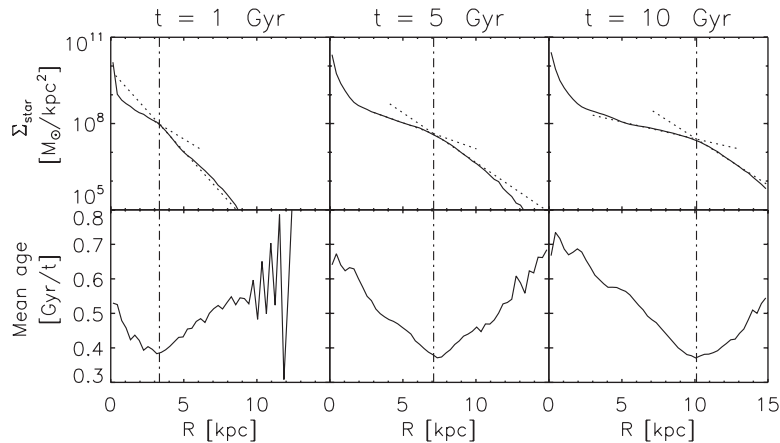


Figure 1. The stellar surface density (top panels) and mean age profiles (bottom panels) at three different times in the simulation. The dashed lines in the upper panels are double exponential fits to the surface density profile. The vertical dashed lines indicate the location of the break in all panels. At all times, the break corresponds to a minimum in the stellar mean age, which arises due to the significant radial migration of stars.

2. Connection Between Radial Migration and Outer Disks

Recently, Roškar et al. (2008) (hereafter R08) investigated the formation of outer disk breaks via N -body + Smooth Particle Hydrodynamics (SPH) simulations of an isolated galaxy forming through dissipational collapse. In the simulation, a break in the stellar mass density profile is seeded by a drop in the star formation rate, which is associated with a rapid drop in the gas surface density. However, the stellar profile extends by several kpc beyond the outermost star forming radius – the outer exponential is populated almost exclusively by stars that migrated there through resonant interactions with spiral arms. Large migrations, which preserve the circularity of stellar orbits, are possible when stars are scattered by the corotation resonance of transient spirals (Sellwood & Binney 2002).

The disk breaks simulated in R08 are therefore a consequence of the interplay between a drop in the star formation rate and secular evolution driven primarily by recurring transient spirals. Figure 1 shows the stellar surface density (top panels) and the associated mean age profiles (bottom panels) at three different times in the simulation. The break in the stellar surface density is associated with an inflection in the mean age profile, which is a direct result of substantial radial redistribution of stellar material. The outer disk thus offers an opportunity to gain insight into the radial migration process, which may significantly affect the entire disk.

3. Observations of Disk Breaks in Support of Radial Migration

Radial migration irreversibly alters the properties of the underlying disk stellar populations. Disentangling the signatures of radial migration in the inner regions of disks, which have been heavily influenced by a myriad of other processes, is nontrivial. It is therefore imperative to attempt to learn about radial migration from the outer disks.

A first clue that the evolution presented in R08 may be common is found in several of the galaxies presented in Wevers et al. (1986), where the drop in gas surface density corresponds to a break in the surface brightness profile and a minimum in the color profile (see, for example, the profiles for NGC 3726, NGC 4242, and NGC 5371). Using multi-band photometry and stellar population synthesis models, MacArthur et al. (2004)

presented radial stellar population trends for a sample of nearby galaxies. From their Figure 20, it is apparent that age minima are common in the radial age profiles for the galaxies in their sample, though it is unclear whether those minima correspond to breaks in the stellar surface brightness. The minima do, in general, appear around 2 - 2.5 disk scale-lengths, which is also roughly the mean break scale radius observed in Pohlen & Trujillo (2006). This suggests that the age minima are indeed associated with profile breaks. A positive age gradient has also been observed beyond the break of M33 via CMD modeling of resolved stellar populations, but this result is also inconclusive because no age information exists for the inner disk regions (Barker et al. 2007). In NGC 7793, the GHOSTS team has observed a flattening of the radial star-count profile beyond the break with increasing age of stellar population, which implies an increasing mean stellar age (de Jong & Radburn-Smith, *private communication*). However, as with the age profile of M33, there is currently no information about the age gradient interior to the break of NGC 7793.

In the case of the edge-on galaxy NGC 4244, observations of resolved stars reveal that the break in the stellar profile occurs in the same place for stars of all ages de Jong et al. (2007). As shown in Figure 2, models presented in R08 naturally give rise to this phenomenon. In the absence of migration, the observed stellar populations of NGC 4244 imply that either the star formation threshold has been in the same place for ~ 10 Gyr, which seems unlikely given that disks are believed to form inside-out (Muñoz-Mateos et al. 2007). Alternatively, the break could have formed on timescales < 100 Myr in order to produce the observed feature (either by dynamics or sudden gas expulsion), which seems highly unlikely given that typical dynamical times in those parts of galactic disks are considerably longer. Efficient radial migration coupled with a star formation threshold therefore provides a very plausible disk break formation mechanism for this particular galaxy.

Azzolini et al. (2008) presented a detailed study of color gradients in a sample of disk galaxies from the GOODS-South field. Their sample includes galaxies in the redshift range $0.1 < z < 1.1$. They find that regardless of redshift, the galaxies with observed downward-bending breaks reveal a minimum in colors roughly analogous to rest-frame $u - g$. Importantly, the color profiles for the anti-truncated disks in their sample show no such feature, arguing against the possibility of a systematic observational error being responsible for the signature. It is possible that the positive color gradient beyond the break is caused by a change in the metallicity gradient. This seems unlikely given that the local sample of MacArthur et al. (2004) shows no pronounced inflections in the metallicity, while age minima are certainly present. According to the authors, the most plausible explanation for the reversal of the color gradient in Azzolini et al. (2008) is that the age of the underlying stellar population increases beyond the break, in line with the theoretical predictions of R08.

In summary, these various observational results strongly imply that radial migration is indeed an important effect at all stages of spiral disk evolution.

4. Conclusions

We have argued that outer disk breaks are a phenomenon that is not only common in observed systems, but that its mechanism of formation may provide important insights into disk evolution as a whole. Substantial observational evidence taken in the context of recent theoretical models suggests that at least a fraction of outer parts of late-type galactic disks form due to substantial radial migration of fully-formed stellar material.

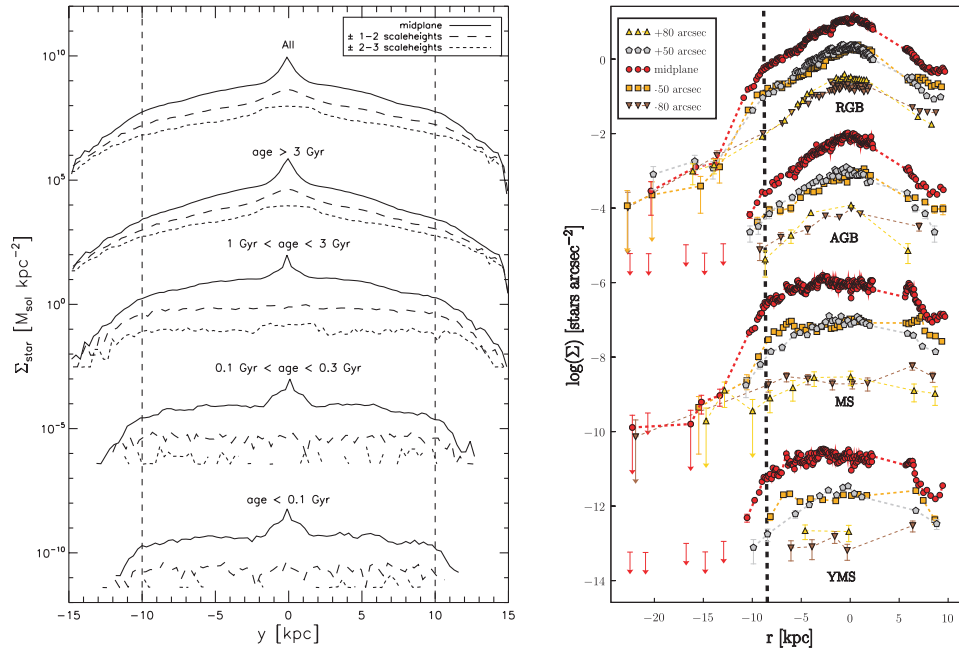


Figure 2. Edge on stellar density profiles from the simulation of Roškar et al. (2008) (left). The break is in the same location regardless of the age of stellar population and height above the plane, consistent with the observations of NGC 4244 (de Jong et al. 2007) (right).

Such evolution affects these extreme outer regions of galaxies, and profoundly impacts the properties of stellar populations in the entire disk.

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